Digital System For The Measurement Of Directivity Index

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An experimental system has been devised for measuring the directivity index of an underwater sound transducer in about 10 minutes, which represents a substantial improvement over the conventional measurement time of at least one hour. This system is designed to measure sound intensity over equal areas of a spherical surface at a fixed radius from the transducer and to calculate directivity index by means of a minicomputer. A seven-element semicircular array of receiving hydrophones provides data for every 10 degrees of azimuth angle. Results of system measurements on several USRD transducers that were within the design limits of the array compared favorably with those obtained by conventional methods and by theoretical predictions. Experimental results were consistent with the findings of an earlier computer simulation study of the problem (NRL Report 7026).

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Abstract

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DIGITAL SYSTEM FOR THE MEASUREMENT OF DIRECTIVITY INDEX

Introduction

Measurement of the directivity index of an underwater electroacoustic transducer has been one of the most time-consuming tasks in the area of sonar transducer calibration. Usually several two-dimensional polar patterns are plotted in various planes to obtain an approximate three-dimensional radiation pattern for the transducer, and then various analog calculation schemes may be used to compute directivity index. This study is concerned with evaluating an experimental digital measurement system for determining directivity index in a matter of minutes.

Results of a computer simulation study of a proposed system for measuring directivity index reported by Poché [1] showed that the required accuracy can be achieved by means of a semicircular array of hydrophones for sampling the acoustic power output of a transducer located at the array's center of curvature. Because each hydrophone of the array sweeps over an equal area of a spherical surface for each increment of angular rotation, accuracy can be controlled by selecting an appropriate number of hydrophones and the sampling frequency. The simulation study showed, for example, that directivity index determinations accurate to within ±0.1 dB could be made with a system of 11 hydrophones (dynamic range $\geq$ 30 dB) sampling 10-deg rotational increments of the surface around a piston transducer of radius 1.59λ ($ka = 10$, where $k = 2\pi/\lambda$, a is the piston radius, and λ is the wavelength of sound in water) radiating in an infinite baffle.

To evaluate the simulation study in practical terms, an automatic sampling system was developed to measure transducer output over equal spherical areas and to transmit the data to a minicomputer for calculation of directivity index. Experimental results obtained with this system are presented and compared with those obtained by theoretical calculations and by conventional measurement methods.

The System

Although the computer simulation study concluded that the proposed directivity index-measuring system required an 11-element array of hydrophones to achieve the desired accuracy, close examination of the data reveals that an array of 7 elements would be sufficient in many cases.

Because the use of fewer elements simplifies some of the design **aspects** and considerably reduces the time required for a complete measurement, a 7-element array was selected for evaluation. Sensors of the array were located at 0, ±16, ±35, and ±59 deg along a semicircular frame (1-m radius) of thin-walled aluminum tubing (2.5 cm outside diameter) as shown in Fig. 1. Each sensor is a capped piezoelectric ceramic cylinder 1.27 cm in diameter by 1.27 cm long with 0.16-cm wall thickness.

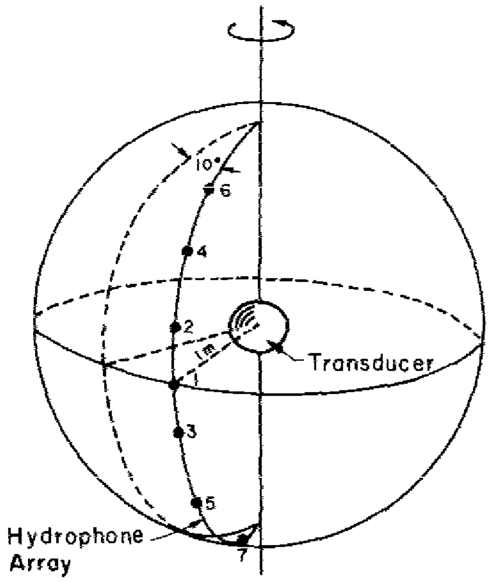


Fig. 1. Hydrophone array for sampling transducer output over equal spherical areas at a radial distance of 1 m.

In this system, the transducer is rotated about the axis formed by the diameter that connects the two ends of the array to produce the same relative motion as rotation of the array. Sampling data from the hydrophones is transmitted by the associated electronic circuitry via punched paper tape to a digital computer programmed to calculate directivity index.

Three major functions are performed by the system electronics: (1) measurement of the output voltages of the array sensors, (2) synchronization of the measurement points with angular rotation of the projector, and (3) formatting data output. A simplified block diagram of the system is shown in Fig. 2. Voltage measurements are made by switching each of the seven hydrophone output signals through an externally triggerable channel scanner into a sampling digital voltmeter (SDVM). A "code wheel" and photoelectric sensors synchronize measurements with rotation.

The code wheel is a slotted aluminum disk mounted on the top of the rotator shaft. Deep slots in the edge of the disk divide it into 10-deg arcs that are subdivided by seven shallower slots spaced 1.4 deg apart. Paired light-emitting diodes (LED's) and phototransistors are positioned to generate pulses when the 10-deg and 1.4-deg slots appear between them as the code wheel turns with the rotator shaft. The 10-deg pulses are used to trigger a counter and record angular position in 10-deg increments, and the 1.4-deg pulses trigger the seven sensor measurements during the time between 10-deg pulses.

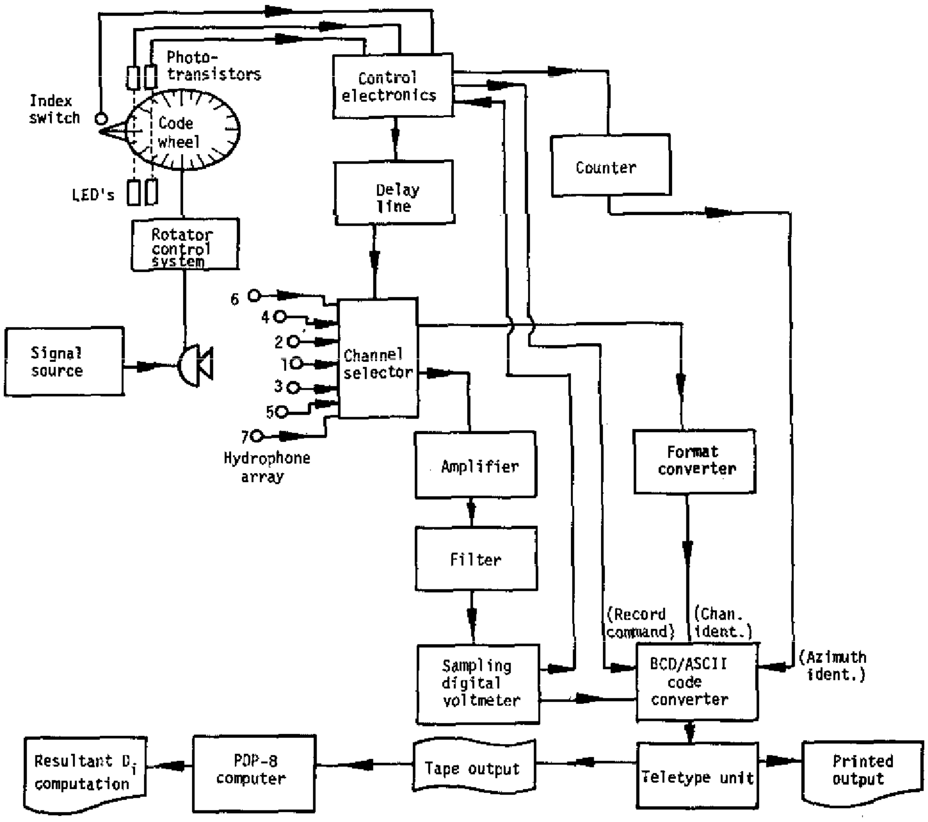


Fig. 2. Simplified block diagram for experimental directivity measurements.

Data outputs from the counter, channel scanner, and SDVM are all in binary-coded decimal (BCD) form; they are translated into Teletype serial ASCII output format by a converter that reads all parallel inputs within approximately 20 ns after receiving a triggering pulse. To ensure that a hydrophone voltage reading is available to the code converter at all times, the SDVM samples continuously at the rate of 100 Hz with a sample gate width of 2 ms.

The system timing sequence is set by combining the 1.4-deg pulse with the inverted SDVM sample gate pulse as the inputs to an AND gate. The AND gate output then is used as the code converter trigger to "strobe" the data out; that is, data are taken only when the trailing edge of the SDVM sample gate and the 1.4-deg pulse are coincident and the code converter is in a "ready" condition. The channel scanner trigger is the 1.4-deg pulse delayed 9 ms from the AND gate input to ensure that switching to the next channel occurs only after completion of the most recent voltage measurement.

When a transducer first is mounted on the rotator shaft, the zero-degree reference of the code wheel is adjusted to coincide with the azimuth angle of maximum projector signal. The system is activated automatically when the zero-degree reference is indicated. Figure 3 is a flow diagram of the system logic. "Wait loops" in the logic provide a margin for error related to variations in the rotator angular velocity; thus, system accuracy is less dependent upon the rotator maintaining a constant angular velocity.

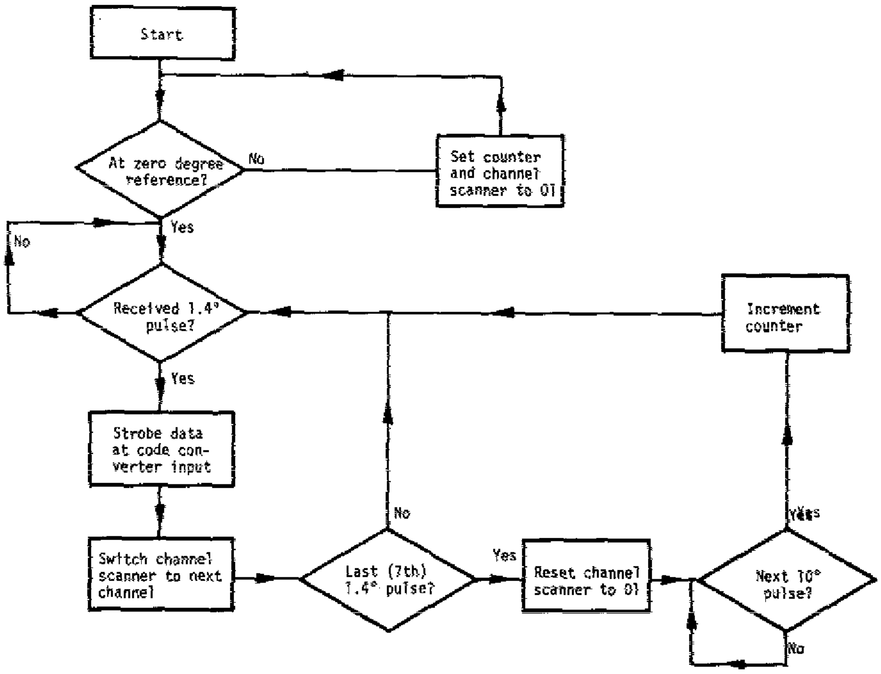


Fig. 3. System timing logic.

The time required to make a complete directivity index measurement is determined primarily by the electromechanical devices used, the channel scanner, and the Teletype. For example, the Teletype requires approximately 1 s to output each 10-character data word. (Ten ASCII characters are used to specify channel, voltage to three significant places, azimuth angle in 10-deg increments, and a space for the data terminator.) The measurement period for each 10-deg segment is 15 ± 1 s, which yields a total measurement time of approximately 9.5 min.

Punched paper tape output from the Teletype is read into a Digital Equipment Corporation PDP-8 computer for the directivity index (D_i) calculation. The data reduction program outputs, in addition to the D_i value, "partial" directivity patterns for the horizontal (XY) and vertical (XZ) planes. The partial patterns are the outputs of the center array sensor in each 10-deg segment (XY) and the seven hydrophone outputs at the azimuth angles 0 and 180 deg (XZ) expressed in decibels referenced to the center hydrophone output at 0 deg. Typical data are presented in Tables I and II.

Table I. Typical horizontal (XY) plane "partial" directivity pattern data from experimental digital measurement system (dB re center hydrophone output at 0 deg).

Array rotational angle (deg)	Partial direct. pattern (dB)	Array rotational angle (deg)	Partial direct. pattern (dB)	Array rotational angle (deg)	Partial direct. pattern (dB)
0	0.0	120	-30.0	240	-30.0
10	-13.0	130	-30.0	250	-30.0
20	-16.1	140	-30.0	260	-30.0
30	-28.5	150	-30.0	270	-30.0
40	-30.0	160	-30.0	280	-30.0
50	-27.1	170	-30.0	290	-30.0
60	-30.0	180	-30.0	300	-30.0
70	-29.3	190	-30.0	310	-30.0
80	-30.0	200	-30.0	320	-23.7
90	-30.0	210	-30.0	330	-27.7
100	-30.0	220	-30.0	340	-20.3
110	-30.0	230	-30.0	350	-12.0

Table II. Typical vertical (XZ) plane "partial" directivity pattern data from experimental digital measurement system (dB re center hydrophone output at 0 deg).

Azimuth angle (deg)	Partial direct. pattern (dB)	Azimuth angle (deg)	Partial direct. pattern (dB)	Azimuth angle (deg)	Partial direct. pattern (dB)
0	0.0	145	-30.0	239	-30.0
16	-14.1	164	-30.0	301	-30.0
35	-30.0	180	-30.0	325	-30.0
59	-30.0	196	-30.0	344	-15.4
121	-30.0	215	-30.0		

The operating frequency range of the system is limited at the low end by surface and bottom reflections, and at the high end by the approximate frequency at which the receiving sensitivities of array elements begin to diverge from one another. The resulting operating bandwidth extends from 10 to 30 kHz. Because the primary function of this system was to provide experimental data by means of the equal-area sampling technique, this limited frequency range was not considered to be severely restrictive. (The system electronics is capable of operating over a much wider frequency range.)

Measurements and Results

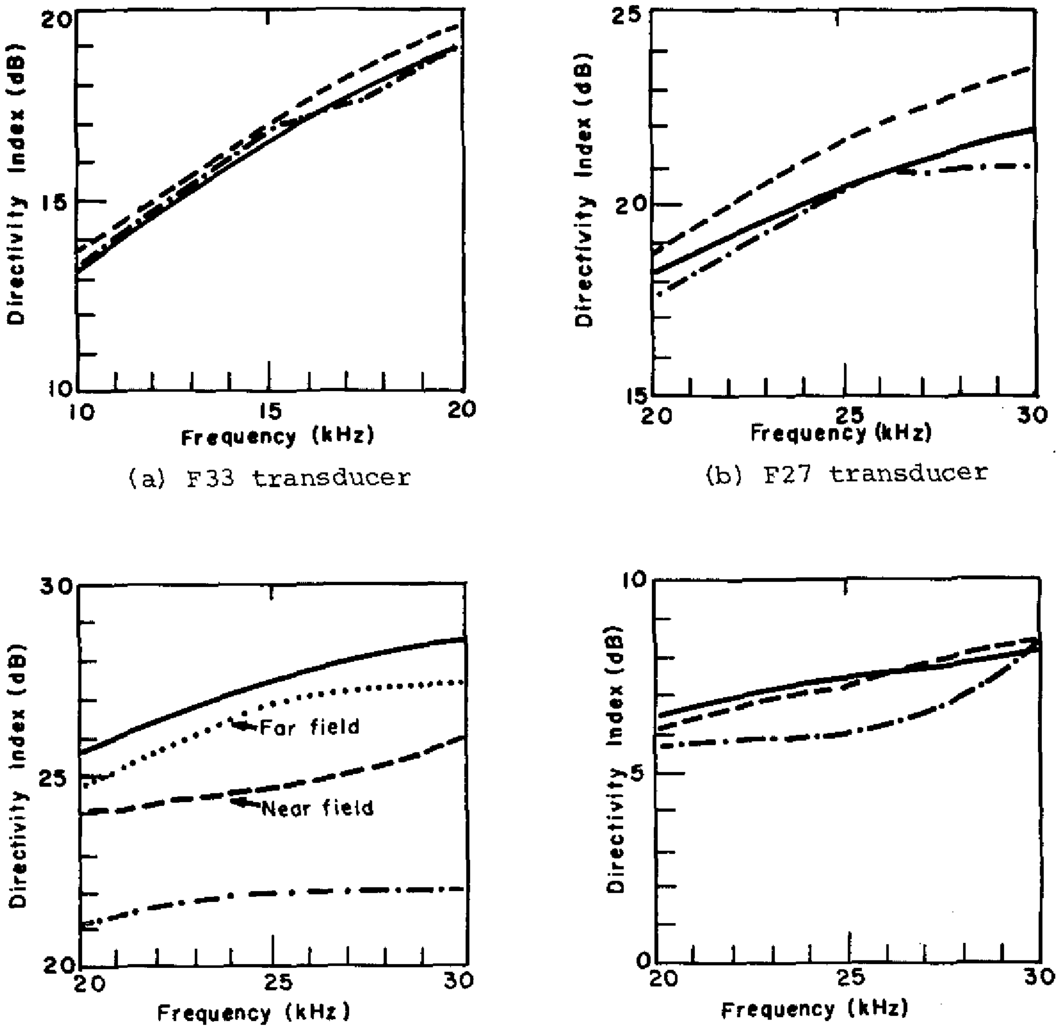
Directivity index values provided by the experimental system were compared with those obtained by using two additional and independent methods: (1) calculation from theoretical approximations [2] and (2) computation from conventionally measured directivity patterns. The directivity patterns were obtained by substituting a single standard hydrophone for the 7-element array. Results from the independent methods were compared with the mean of five or more complete measurements with the experimental system for each frequency point sampled.

Four transducers representative of types and sizes suitable for the frequency range of the system were selected for comparative evaluations. The USRD type F33 transducer was included in this group because of its similarity to the idealized piston used in the computer simulation of this system. This transducer is a 21.3-cm-diam piston, for which ka varies from 4.4 to 9.0 in the frequency range from 10 to 20 kHz. Results of D_i measurements for the F33 are shown in Fig. 4(a).

The USRD type F27 transducer is a piston device of similar size but of slightly different configuration, for which ka values range from 8 (at 20 kHz) to 20 (at 30 kHz); results of D_i measurements are shown in Fig. 4(b).

Results for the F33 and F27 transducers indicate that as long as the requirement $ka \leq 10$ is satisfied, the calculated and measured values agree quite well. In comparing the data, it should be noted that the value computed from the conventional directivity patterns represents 144 equal-angle points over two perpendicular planes through the sphere (data points taken every 5 deg on both XY and XZ patterns for each frequency), but the experimental system value represents 252 points of equal area over the sphere. The effect of the more uniform sampling inherent in the equal-area method is evident in Fig. 4(b). Figures 5(a) and 5(b) show the partial patterns generated by the system data superimposed on the measured horizontal patterns.

Figure 4(c) presents the results of measurements on the USRD type F22 piston transducer, which is too large ($28.5 > ka > 19$) for the array in the 20- to 30-kHz range. Measurements made at the fixed array radius provide data for the near-field directivity pattern; far-field values of



(a) F33 transducer

(b) F27 transducer

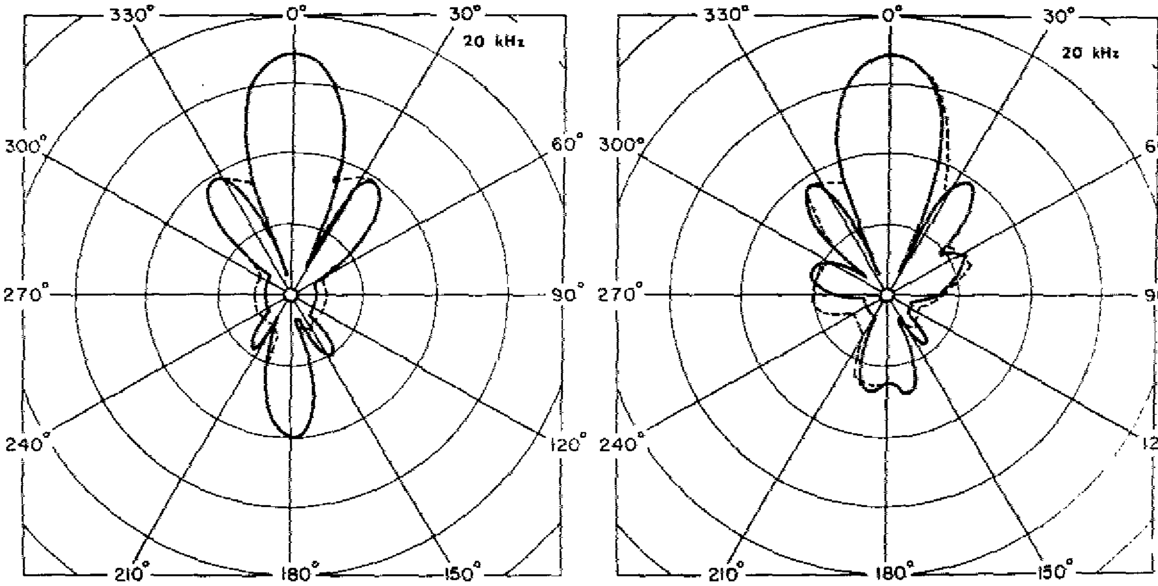
(c) F22 transducer

(d) F37 transducer

Fig. 4. Comparison of directivity index system measurements (•—•) with results of theoretical approximations (——) and values calculated from directivity patterns (---).

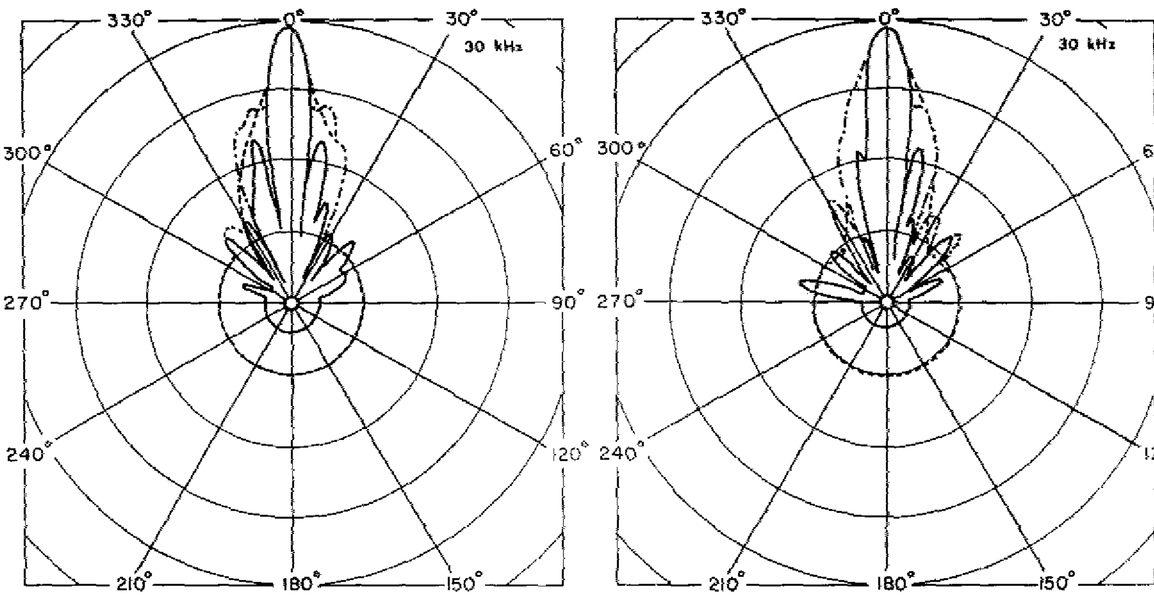
D_i presented in Fig. 4 were computed from the horizontal and vertical patterns measured at 5 m. Figures 6(a) and 6(b) show the far-field patterns and the partial patterns superimposed on the near-field horizontal and vertical patterns. For all three piston transducers, the five or more complete system measurements at each frequency point produced D_i values that were repeatable to within ±0.1 dB.

The fourth transducer used in evaluating the system was the USRD type F37, a 16.5-cm uniform line, which is of particular interest because of its characteristic toroidal directivity pattern (omnidirectional in the



(a) F33 transducer, XY plane (b) F27 transducer, XY plane

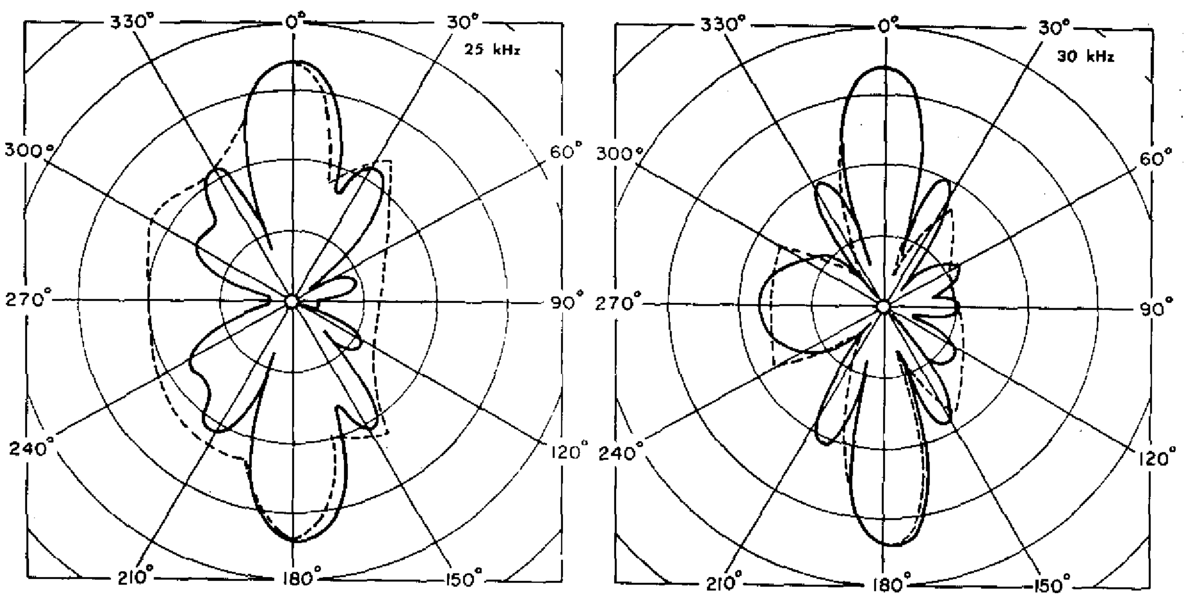
Fig. 5. Comparison of directivity patterns, F33 and F27 transducers; partial patterns from experimental system data (---) superimposed on conventionally measured horizontal patterns (——). Center to outer circle of grid, each pattern, equals 40 dB.



(a) F22 transducer, XY plane (b) F22 transducer, XZ plane

Fig. 6. Comparison of directivity patterns, F22 transducer; partial patterns from experimental system data (---) and far-field patterns (——) superimposed on near-field patterns (•—•). Center to outer circle of grid, each pattern, equals 40 dB.

horizontal plane and directional in the vertical plane, with the axis of symmetry coicident with the cylindrical axis). Figure 4(d) shows that the values computed from the directivity patterns are in good agreement with the theoretical calculations; agreement between these results and those measured with the experimental system appears to improve with increasing frequency. A possible explanation is that the data may include interference (reflection) phenomena caused by the combination of two conditions: (1) the measurements were made in shallow water (8-9 m) and (2) the line becomes more nearly omnidirectional in the vertical plane as frequency decreases so that at low frequencies more power is radiated toward the surface and the bottom. Figures 7(a) and 7(b) lend some validity to this conclusion. At the lower frequency (25 kHz), the system seems to be "seeing" a more nearly omnidirectional pattern than is actually present, particularly in the direction of the lake bottom. A less directional pattern obviously would be associated with a lower D_i value. Measurements made at the higher frequency show a marked reduction in this effect. Repeated measurements at any single frequency produced D_i values consistent within ±0.2 dB. In Figs. 5, 6, and 7 the partial patterns indicated by the dashed line represent the envelope defined by the measured points rather than continuous measurements.



(a) F37 transducer, XZ plane (b) F37 transducer, XZ plane

Fig. 7. Comparison of directivity patterns, F37 transducer; partial patterns from experimental system data (---) superimposed on conventionally measured patterns (——). Center to outer circle of grid, each pattern, equals 40 dB.

Conclusions

A system that samples equal areas of a sphere to determine the directivity index of an underwater sound transducer is feasible and yields experimental data consistent with that predicted by a computer simulation study. The versatility of such a system, however, is severely limited by the restrictions placed upon it by the hydrophone array. That is, it is theoretically possible to design an array to sample accurately the far-field directivity of a transducer of any size and complexity, but there are practical limitations to the physical size of the array and the number of elements that can be used. An array of moderate size with a reasonable number of elements, however, could be used to fulfill most requirements. The technique is most feasible when many measurements are required on a large number of similar transducers.

Any attempt to design a permanent measurement system should include some obvious and basic changes from the system used in this investigation. For example, array hydrophone elements should be useful over a wider frequency range. Much faster switching of array hydrophone signals also would be desirable, and output should be directed to a faster peripheral device or directly interfaced to a digital computer.

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[2] R. J. Bobber, *Underwater Electroacoustic Measurements* (Naval Research Laboratory, Government Printing Office, Washington, 1970), pp. 76-90.